REGULATOR DESIGN FOR A POWER SYSTEM WITH CONSTANT LOCAL LOAD DISTURBANCES

A Thesis Submitted
In Partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

By
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to the

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR
JANUARY, 1978

CERTIFICATE

It is certified that this work entitled 'Regulator design for a power system with constant local load disturbances' by N.K. Patel has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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ACKNOWLEDGEMENT

I will always be grateful to my supervisor Prof. S.S. Prabhu. His constructive criticism, suggestions and encouragement has been invaluable during all phases of this work.

I would like to thank all my friends especially Sachchidanand, Goyal, Achla, Binoy and B. Srinivasan for the help rendered for the completion of the programme.

My thanks are due to Mr. Vijay Kumar Dadwal for the care and interest taken in typing and Mr. R. Prasad for skilful cyclostyling.

Lastly, I would thank Shaila : who has been a source of inspiration for me.

Nalini Kumar Patel

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LIST OF PRINCIPAL SYMBOLS

$\bar{A}$: (n+m)(n+r) augmented system matrix

$\bar{B}$: (n+m) r augmented system control matrix

I : identity matrix of appropriate dimension

J : objective function for optimization

K : feedback matrix of appropriate dimension

P : (n+m) vector of augmented system state variables

Q : r - vector of augmented system control variables

S : set of system equations

λ : eigen values of the system matrix

ρ : new eigen value location to be assigned

A dot over a symbol or a prefix p denotes first derivative with respect to time

Two dots over a symbol denotes second derivative with respect to time

A subscript T denotes transpose

$R + jX_l$; local load impedance

X : tie line reactance

X_{ffd} : field winding reactance

X_{fl} : field winding leakage reactance

X_{md} : d - axis mutual reactance

X_d : d - axis synchronous reactance

X_{kkd} : d - axis damper winding reactance

X_{d1} : d - axis leakage reactance

X_q : q - axis synchronous reactance

X_{kkq} : q - axis damper winding reactance

X_{mq} : q - axis mutual reactance

V_o : infinite bus voltage

V_{fd} : field winding voltage

e_t : generator terminal voltage

e_d : d - axis component of the generator terminal voltage

e_q : q - axis component of the generator terminal voltage

T_m : inertial constant

K_d : damping constant

T_i : input torque

r_{fd} : field winding resistance

r_{kd} : d - axis damper winding resistance

r_{kq} : q - axis damper winding resistance

w_o : synchronous speed rad/sec.

Ψ_{fd} : field winding flux linkage

Ψ_d : direct axis flux linkage

Ψ_{kd} : d - axis damper winding flux linkage

Ψ_q : q - axis flux linkage

Ψ_{kq} ; q - axis damper winding linkage

τ_g : primemover and governor time constant

τ_e : exciter time constant

δ_m : machine load angle

δ_2 : load angle between generation bus and infinite bus

δ : load angle between generator and infinite bus

δ_1 : load angle between generator and the terminal of Thevenin equivalent network.

ABSTRACT

The basic aim of this thesis has been to design regulator and stabilizer for asymptotic rejection of constant disturbances in a local load connected to a generation bus from the infinite bus and obtain improved dynamic behaviour of a given power system. An appropriate linearized model of the given system is developed. Optimal modal control theory is used to optimize the controller parameters. The system performance with various controller schemes are discussed.

CHAPTER 1

INTRODUCTION

Advances in the technolcgy of energy conversion, characterized by increased sizes, pressures, and temperatures of steam generating units and large hydel units have resulted in bulk power generation and transmission. In recent decades substantial increase in reliability and reduction in cost are being achieved by interconnexion of these generating units. The fundamental problem in the design and operation of such systems are those associated with system stability, economic operation, reliability of supply to the consumers and security. Furthermore system voltages and frequency are to be constrained to be within specified limits. Many of these problems can be posed as problems in the area of automatic control.

Modern control theory offers various techniques for the solution of such problems. Among these the application of Modal control theory [1] results in simplified and efficient techniques to develop designs of regulators for complex systems of large order. Simple design techniques are available in literature [2] for realizing optimal modal controllers.

The design of regulators is nearly always based on linearized system models [3]. Such models are always in - accurate. Inaccuracies may arise from approximations made in the theoretical description of the system, from linearizing a nonlinear model about an operating point, from simpli-

fying a higher order model to obtain one amenable to analysis, from errors in parameter identification and from many other sources. In addition the systems to be controlled are subject to disturbances, usually unmeasurable, and to changes in inputs and set points.

Linearized models are generally used to design power system controllers. Often, reduced order models of these linearized models are used to simplify the computations involved.

In practice power systems are subject to a large class of disturbances. Disturbances of impulsive nature consist of those due to lightning strokes and instantaneous short circuits in transmission lines. Switching on or off of loads, change in impedance due to removal of faulted lines and many sustained faults contribute to step (that is, constant) disturbance. Beyond these the system encounters arbitrary disturbances due to hunting in the generators, arcing ground in transmission lines, power swings etc., many of which can be approximated in the class of polynomial disturbances for the sake of analysis and design.

With such a system with frequent disturbances of a large class the aim of a satisfactory regulator design consists of determining controllers that yield good transient response and maintain output regulation, keeping in mind the simplicity and economy of the scheme.

C.D. Johnson [4] considered the case of external disturbances which are not directly measurable but can be represented as m^{th}- degree polynomials in time with unknown coefficients. The work has been extended by the author [5] to accamodate the case of unmeasurable vector disturbances satisfying a ρ^{th}- degree linear differential equation with known coefficients and vector control. Davison and Smith [6] have found conditions for existance of a feed-back control system of minimum order for closed loop pole placement and output regulation in presence of constant external disturbance. The same authors give design methods [3] for linear regulators of both integral feed back and feed forward types for linear time invariant multivariable systems with constant disturbance. Davison [7] has considered the case of assymptotic rejection of any measurable disturbance by use of feed forward control for multivariable linear time invarient systems. Davison and Smith [8] have also obtained explicit feed forward and integral feed back controllers for linear time invariant multivariable plants, subject to both measurable and unmeasurable constant disturbances, so that the outputs are regulated to preassigned set points.

This work considers a power system, consisting of a single generator connected to infinite bus system with a local load at the generation bus. Controllers are designed for constant disturbance in the local load so that the infinite

bus system gets decoupled from the local load disturbances in steady state and asymptotic regulation of voltage is obtained at the generation bus. Further more transient response of the system is improved by appropriate closed loop pole placement.

CHAPTER 2

PROBLEM FORMULATION

2.1 INTRODUCTION

The system under consideration (Fig. 2.1) consists of a generator connected to a local load at the generation bus and a tie line connecting the generator to the infinite bus. The fluctuations in the local load get reflected on the generator as well as the infinite bus system. The system, though considered to be infinite is in practice a finite one and the disturbance in the local load is transmitted even to the remote ends of the whole system, there by, bringing down the stability limit and the maximum power flow in any part of it.

The problem comprizes of regulating the generation bus voltage and the power angle so that the disturbances in the local load are constrained to the local generator only there by improving the overall system performance. The class of constant disturbances is considered for the controller design; impulsive disturbances are taken care of by the design of a stable system with good transient response.

Optimal modal control theory is used for designing three types of controllers , namely

(i) Feed forward controller

(ii) Integral feed back controller

(iii)Combined feed forward and integral feed back controller

The efficacy of the various schemes is studied.

The above controller schemes are briefly discussed below.

2.2 INTEGRAL FEED BACK AND FEED FORWARD CONTROLLERS [3], [4]:

Consider the system:

$$S: \quad \begin{aligned} \dot{X} &= AX + BU + DW \\ Y &= CX + EU + FW \end{aligned} \tag{2.1}$$

where X is the n-state vector, U the r-plant input vector, Y the m-output vector and W is the q-constant disturbance vector. A, ..., F are real constant matrices of appropriate dimensions. Assume without loss of generality that the system S is expressed in the minimal form, i.e.

$$\text{Rank} \begin{bmatrix} A & B & D \\ C & E & F \end{bmatrix} = n + m \tag{2.2}$$

It is desired to find a linear time invariant controller for S such that $Y(t) \to 0$ as $t \to \infty$ and the closed loop system is stable.

Necessary and sufficient conditions for a solution to the problem to exist are:

(i) (A, B) is stabilizable

(ii) $\text{Rank} \begin{bmatrix} A & B \\ C & E \end{bmatrix} = n + m \qquad (2.3)$

It may be noted that the condition (ii) implies that $r \geq m$.

We may further stipulate that the transient response of the closed loop system should be satisfactory. This will require assignment of closed loop eigen values to appropriate locations. This condition will require controllability of the dominant eigen values of the open loop system.

Assuming the above conditions to hold, let the desired final (steady state) values of X, Y and U be $\bar{X}$, $\bar{Y}$ and $\bar{U}$ respectively.

In steady state $\dot{X} = 0$, and $Y = 0$ (by design requirement).

In steady state equns. (2.1) reduce to

$$\begin{aligned} A\bar{X} + B\bar{U} + DW &= 0 \\ C\bar{X} + E\bar{U} + FW &= 0 \end{aligned} \qquad (2.4)$$

Solving for $\bar{X}$ and $\bar{U}$

$$\begin{bmatrix} \bar{X} \\ \bar{U} \end{bmatrix} = - G^T (G\ G^T)^{-1} \begin{bmatrix} D \\ F \end{bmatrix} W \qquad (2.5)$$

where

$$G \triangleq \begin{bmatrix} A & B \\ C & E \end{bmatrix}$$

Defining $Z = X - \bar{X}$, $V = U - \bar{U}$ and letting $P = \begin{bmatrix} \dot{Z} \\ Y \end{bmatrix}$ and $Q = \dot{V}$ we obtain, from eqns. (2.1), for the case of constant disturbance

$$\dot{P} = \begin{bmatrix} \ddot{Z} \\ \dot{Y} \end{bmatrix} = \begin{bmatrix} A & 0 \\ C & 0 \end{bmatrix} P + \begin{bmatrix} B \\ E \end{bmatrix} Q \qquad (2.6)$$

Let $\quad \bar{A} \triangleq \begin{bmatrix} A & 0 \\ C & 0 \end{bmatrix}$ and $\bar{B} \triangleq \begin{bmatrix} B \\ E \end{bmatrix}$

From equn. (2.6) we have

$$\dot{P} = \bar{A}\, P + \bar{B}\, Q \tag{2.7}$$

Assuming a linear control law,

$$Q = K\, P$$

for the system described by equn. (2.7) we obtain

$$\dot{V} = K_1 \dot{Z} + K_2 Y \tag{2.8}$$

where

$$K \triangleq \left[K_1 \;\vdots\; K_2 \right]$$

Integrating eqn. (2.8) and substituting for V and Z .

we obtain

$$U = K_1 X + K_2 \int_0^t Y(s)ds - K_1 \bar{X} + \bar{U} \tag{2.9}$$

From eqn. (2.9) and (2.5) we obtain

$$U = K_1 X + K_2 \int_0^t \check{Y}(s)ds + K_3 W \tag{2.10}$$

where

$$K_3 \triangleq \left[K_1 \;\vdots\; -I \right] G^T \left[G\, G^T \right]^{-1} \begin{bmatrix} D \\ F \end{bmatrix}$$

The state feed back $K_1 X$ is used to place properly the dominant eigen values of the system matrix A to achieve desired transient response.

The different control schemes that can be implemented are :

(i) Feed forward control

$$U = K_1X + K_3W \tag{2.11}$$

(ii) Integral feed back control

$$U = K_1X + K_2 \int_0^t Y(s)ds \tag{2.12}$$

(iii) Combined feed forward and Integral feed back control

$$U = K_1X + K_2 \int_0^t Y(s)ds + K_3W \tag{2.13}$$

The control schemes (i) and (iii) necessiate that the disturbances be measurable.

Optimal modal control theory can be successfully used to evaluate the feed back matrix.

2.3 SYSTEM MODEL

Our system comprizes of a synchronous generator with an exciter and a governor and primemover. The generator is connected to the infinite bus system by a tie line with negligible resistance. At the generation bus a load is connected which is subject to disturbances. The load is represented by constant impedance for the design and the disturbances are assumed to be constant.

A model linearized about an operating point is obtained for the above system.

2.3.1 Load Representation

Representing the terminal network by its Thevenin's

$$R^1 + jX^1 = BX + jAX$$
$$V^1 = AV + jBV_o \qquad (2.14)$$

where

V^1 represents the equivalent voltage source

$R^1 + jX^1$ is the equivalent series impedance

$$A \triangleq \frac{R^2 + X(X + X_1)}{R^2 + (X + X_1)^2}$$

$$B \triangleq \frac{RX}{R^2 + (X + X_1)^2}$$

2.3.2 Machine Equations [9] :

$$\psi_{fd} = X_{ffd}\, i_{fd} + X_{md}\, i_{kd} - X_{md}\, i_d$$
$$\psi_d = X_{md}\, i_{fd} + X_{md}\, i_{kd} - X_d\, i_d$$
$$\psi_{kd} = X_{md}\, i_{fd} + X_{kkd}\, i_{kd} - X_{md}\, i_d$$
$$\psi_q = X_{mq}\, i_{kq} - X_q\, i_q$$
$$\psi_{kq} = X_{kkq}\, i_{kq} - X_{mq}\, i_q \qquad (2.15)$$

$$v_{fd} = \frac{1}{w_o}\, p\, \psi_{fd} + r_{fd}\, i_{fd}$$

$$e_d = \frac{1}{w_o}\, p\, \psi_d - r\, i_d - \frac{w}{w_o}\, \psi_q$$

$$0 = \frac{1}{w_o}\, p\, \psi_{kd} + r_{kd}\, i_{kd}$$

$$T_m \frac{d^2\delta}{dt^2} + k_d \frac{d\delta}{dt} + \psi_d\, i_q - \psi_q\, i_d = T_i$$

The terminal equations are [10] :

$$e_t^2 = e_d^2 + e_q^2$$

$$e_d = V_d^1 + pi_d\, X^1/w_o + R^1\, i_d - X^1\, i_q\, w/w_o \quad (2.16)$$

$$e_q = V_q^1 + pi_q\, X^1/w_o + R^1\, i_q + X^1\, i_d\, w/w_o$$

where (Fig. 2.3) ,

$$V_d^1 = -V^1 \text{ Sin } \delta_1 = -V^1 \text{ Sin } (\delta + \tan^{-1} B/A)$$

$$V_q^1 = V^1 \text{ Cos } \delta_1 = V^1 \text{ Cos } (\delta + \tan^{-1} B/A)$$

$$V^1 = \sqrt{A^2 + B^2} \quad V_o$$

$$\delta_1 = \delta + \tan^{-1} B/A$$

Taking the machine currents, load angle 'δ' and machine speed 'w' as the state variables and eleminating the non-state variables from the above sets of equations and with appropriate substitution for the terminal voltages we obtain the equations:

$$X_{ffd}\, p\, i_{fd} + X_{md}\, p\, i_{kd} - X_{md}\, p\, i_d = w_o (V_{fd} - r_{fd}\, i_{fd})$$

$$X_{md}\, p\, i_{fd} + X_{md}\, p\, i_{kd} - (X_d + X^1) p\, i_d = w_o \Big[- \sqrt{A^2 + B^2}$$

$$\times V_o \,\mathrm{Sin}\, (\delta + \tan^{-1} B/A) + (R^1 + r)\, i_d +$$

$$\frac{w}{w_o} (X_{mq}\, i_{kq} - (X^1 + X_q)\, i_q) \Big]$$

$$X_{md}\, p\, i_{fd} + X_{kkd}\, p\, i_{kd} - X_{md}\, p\, i_d = -w_o r_{kd}\, i_{kd} \qquad (2.17)$$

$$X_{mq}\, p\, i_{kq} - (X_q + X^1)\, p\, i_q = w_o \Big[\sqrt{A^2 + B^2}\, V_o$$

$$\times \mathrm{Cos}\, (\delta + \tan^{-1} B/A) + (R^1 + r)\, i_q -$$

$$\frac{w}{w_o} (X_{md}\, i_{fd} + X_{md}\, i_{kd} - (X_d + X^1)\, i_d) \Big]$$

$$X_{kkq}\, p\, i_{kq} - X_{mq}\, p\, i_q = -w_o\, r_{kq}\, i_{kq}$$

$$p\, \delta = w - w_o$$

$$T_m\, p\, w = T_i - k_d\, (w - w_o) + (X_{md}\, i_{fd} + X_{md}\, i_{kd} -$$

$$X_d\, i_d)\, i_q - (X_{mq}\, i_{kq} - X_q\, i_q)\, i_d$$

2.3.3 Voltage regulator [9] (fig. 2.4) :

The voltage regulator is represented by a linear model with an internal stabilizer loop:

$$\tau_e \, p \, E_{fd} = k_e (V_{ref} - e - V_s) - E_{fd}$$

$$\tau_s \, p \, V_s = k_s \, p \, E_{fd} - V_s \qquad (2.18)$$

$$V_{fd} = \frac{r_{fd}}{X_{md}} \, E_{fd}$$

2.3.4 Primemover and governor [11] (fig. 2.5) :

The primemover and the governor are represented by a single time constant. The governing equation is taken to be:

$$p \, \Delta T_{ing} = \frac{1}{\tau_g} \Delta T_{ing} - \frac{\Delta T_i}{\tau_g} \qquad (2.19)$$

2.3.5 System state equations:

The above equations (2.17) - (2.19) representing the system are a set of non-linear equations. These equations are linearized about an operating point. The operating point quantities are denoted by the subscript '0' and the incremental quantities about the operating point by the prefix 'Δ'. Expanding in Taylor series and taking the first order approximation the set of equations reduce to :

$$\frac{1}{w_o} G_1 \dot{X} = A_1 X + B_1 U + D_1 W \qquad (2.20)$$

where

X is the statevector : $\left[\Delta i_{fd} , \Delta i_{kd} , \Delta i_d , \Delta i_{kq} , \Delta i_q , \Delta \delta , \Delta w , \Delta T_i , \Delta E_{fd} , \Delta V_s\right]^T$

U is the control vector : $\left[\Delta E , \Delta T_{ing}\right]^T$

W is the disturbance vector : $\left[\Delta R , \Delta X_L\right]^T$

$$G_1 \triangleq \begin{bmatrix}
X_{ffd} & X_{md} & -X_{md} & & & & & & & \\
X_{md} & X_{md} & -(X_d+X_o^1) & & & & & & & \\
X_{md} & X_{kkd} & -X_{md} & & & & & & & \\
 & & & X_{mq} & -X_q+X_o^1 & & & & & \\
 & & & X_{kkq} & -X_{mq} & & & & & \\
 & & & & & w_o & & & & \\
 & & & & & & w_o T_m & & & \\
 & & & & & & & w_o \tau_g & & \\
 & & & & & & & & w_o \tau_e & \\
 & & & & & & & & & w_o \tau_s
\end{bmatrix}$$

The non-zero entries of A_1 , B_1 and D_1 are :

$A_1(1 , 1) = -r_{fd}$

$A_1(1 , 9) = r_{fd}/X_{md}$

$A_1(2 , 3) = R_o^1 + r$

$A_1(2 , 4) = X_{mq}$

$A_1(2 , 5) = -(X_o^1+X_q)$

$A_1(2 , 6) = -V_o C_{10}$

$A_1(2 , 7) = -(X_q+X_o^1)\ i_{qo}/w_o$

$A_1(3 , 2) = -r_{kd}$

$A_1(4 , 1) = -X_{md}$

$A_1(5 , 4) = -r_{kq}$

$A_1(6 , 7) = 1.0$

$A_1(7 , 1) = X_{md}\ i_{qo}$

$A_1(7 , 2) = X_{md}\ i_{qo}$

$A_1(7 , 3) = (X_q-X_d)\ i_{qo}$

$A_1(7 , 4) = -X_{mq}\ i_{do}$

$A_1(7 , 5) = X_{md}\ i_{fdo}+(X_q-X_d)\ i_{do}$

$A_1(7 , 7) = -kd$

$A_1(7 , 8) = 1.0$

$A_1(4 , 2) = -X_{md}$ $\qquad$ $A_1(8 , 8) = -1.0$

$A_1(4 , 3) = X_d + X_o^1$ $\qquad$ $A_1(9 , 9) = -1.0$

$A_1(4 , 5) = R_o^1 + r$ $\qquad$ $A_1(9 , 10) = -K_e$

$A_1(4 , 6) = -V_o C_{20}$ $\qquad$ $A_1(10 , 9) = -K_s/\tau_e$

$A_1(4 , 7) = (-X_{md} i_{fd} + (X_d + X_o^1) i_{do})/w_o$ $\qquad$ $A_1(10 , 10) = -\dfrac{K_e K_s}{\tau_e} - 1$

$B_1(9 , 1) = -K_e$ $\qquad$ $B_1(10 , 1) = -\dfrac{K_e K_s}{e}$ $\qquad$ $B_1(8 , 2) = 1.0$

$$D_1(2 , 1) = R_{20}(-V_o A_{10} - X\, i_{qo}) + R_{10}(X\, i_{do} + V_o B_{10})$$

$$D_1(3 , 1) = R_{20}(X\, i_{do} + V_o A_{20}) + R_{10}(X\, i_{qo} + V_o B_{20})$$

$$D_1(2 , 2) = X_{20}(-V_o A_{10} - X\, i_{qo}) - X_{10}(X\, i_{do} + V_o B_{10})$$

$$D_1(3 , 2) = X_{20}(X\, i_{do} + V_o A_{20}) - X_{10}(X\, i_{qo} + V_o B_{20})$$

where,

$$A_{10} = \frac{\mathrm{Sin}(\delta_o + \tan^{-1} B_o/A_o) A_o}{\sqrt{A_o^2 + B_o^2}} - \sqrt{A_o^2 + B_o^2}\, \mathrm{Cos}(\delta_o + \tan^{-1} B_o/A_o)\, \frac{B_o}{A_o^2} \,\cdot$$

$$\mathrm{Cos}^2(\tan^{-1} B_o/A_o)$$

$$B_{10} = \frac{B_o \mathrm{Sin}(\delta_o + \tan^{-1} B_o/A_o)}{\sqrt{A^2 + B^2}} + \frac{\sqrt{A_o^2 + B_o^2}}{A_o}\, \mathrm{Cos}^2(\tan^{-1} B_o/A_o) \,\cdot$$

$$\mathrm{Cos}(\delta_o + \tan^{-1} B_o/A_o)$$

$$C_{10} = \sqrt{A_o^2 + B_o^2}\ \mathrm{Cos}(\delta_o + \tan^{-1} B_o/A_o)$$

$$A_{20} = \frac{A_o}{\sqrt{A_o^2 + B_o^2}}\ \mathrm{Cos}(\delta_o + \tan^{-1} B_o/A_o) + \frac{B_o\sqrt{A_o^2 + B_o^2}}{A_o^2} \mathrm{Cos}^2(\tan^{-1} B_o/A_o).$$

$$\mathrm{Sin}(\delta_o + \tan^{-1} B_o/A_o)$$

$$B_{20} = \frac{B_o}{\sqrt{A_o^2 + B_o^2}}\ \mathrm{Cos}(\delta_o + \tan^{-1} B_o/A_o) - \frac{\sqrt{A_o^2 + B_o^2}}{A_o}\ \mathrm{Cos}^2(\tan^{-1} B_o/A_o).$$

$$\mathrm{Sin}(\delta_o + \tan^{-1} B_o/A_o)$$

$$C_{20} = \sqrt{A_o^2 + B_o^2}\ \mathrm{Sin}(\delta_o + \tan^{-1} B_o/A_o)$$

$$R_{10} = \frac{B_o}{R_o} - \frac{2\ B_o^2}{X}$$

$$X_{10} = \frac{2(X + X_1)\ B_o^2}{R_o\ X}$$

$$R_{20} = \frac{2\ B_o}{X}(1 - A_o)$$

$$X_{20} = \frac{B_o}{R_o}\left((1 + A_o)\left(1 + \frac{2\ X_{1o}}{X}\right) + A_o\right)$$

2.3.6 <u>System output equations :</u>

In the problem posed the variables to be regulated are generation bus voltage and the load angle between the generation

and the infinite bus voltages. Thus the output vector $Y = [\Delta\delta_2 \ \Delta e_t]^T$.

where ;

$$\delta_2 \triangleq \delta - \delta_m$$

$$\Delta\delta_2 \triangleq \Delta\delta - \Delta\delta_m \qquad (2.21)$$

$$\Delta e_t = \frac{e_{do}}{e_{to}} \Delta e_d + \frac{e_{qo}}{e_{to}} \Delta e_q$$

Substituting for e_d , e_q from eqns (2.16) , $\delta_m = \mathrm{Cos}^{-1} e_q/e_t$ (fig.2.3) and expressing eqns. (2.21) in terms of the state, control and disturbance variables we obtain :

$$Y = CX + EU + FW \qquad (2.22)$$

where,

$$C(1\ ,\ 1) = \frac{X_o^1\ A(5\ ,\ 1)}{w_o E_{10}}\ , \quad C(1\ ,\ 2) = \frac{X_o A(5\ ,\ 2)}{w_o E_{10}}\ ,$$

$$C(1\ ,\ 3) = rE_{10} \tan Z_o + \frac{X_o^1}{E_{10}} + \frac{X_o^1\ A(5\ ,\ 3)}{w_o E_{10}}\ ,$$

$$C(1\ ,\ 4) = \frac{X_o^1\ A(5\ ,\ 4)}{w_o E_{10}}\ , \quad C(1\ ,\ 5) = -X_q E_{10} \tan Z_o + \frac{R_o^1}{E_{10}} + \frac{X_o^1\ A(5\ ,\ 5)}{w_o E_{10}}$$

$$C(1\ ,\ 6) = 1.0 - \frac{V_o C_{20}}{E_{10}} + \frac{X_o^1\ A(5\ ,\ 6)}{w_o E_{10}}\ ,$$

$$C(1\ ,\ 7) = \frac{X_o^1}{w_o E_{10}}\ (i_{do} + A(5\ ,\ 7))\ ,$$

$$C(1\ ,\ 8) = \frac{X_o^1\ A(5\ ,\ 8)}{w_o E_{10}}\ ,\quad C(1\ ,\ 9) = -\frac{X_o^1\ A(5\ ,\ 9)}{w_o E_{10}}\ ,$$

$$C(1\ ,\ 10) = \frac{X_o^1\ A(5\ ,10)}{w_o E_{10}}\ ,$$

$$E(1\ ,\ 1) = \frac{X_o^1\ B(5\ ,\ 1)}{w_o E_{10}}\ ,\quad E(1\ ,\ 2) = \frac{X_o^1\ B(5\ ,\ 2)}{w_o E_{10}}\ ,$$

$$F(1\ ,\ 1) = \frac{X_o^1\ D(5\ ,\ 1)}{w_o E_{10}} + \frac{P_{40}}{E_{10}}\ ,\quad F(1\ ,\ 2) = \frac{X_o^1\ D(5\ ,\ 2)}{w_o E_{10}} + \frac{X_{40}}{E_{10}}\ ,$$

$$C(2\ ,\ 1) = C_{30}\ A(3\ ,\ 1) + C_{40}\ A(5\ ,\ 1)$$

$$C(2\ ,\ 2) = C_{30}\ A(3\ ,\ 2) + C_{40}\ A(6\ ,\ 3)$$

$$C(2\ ,\ 3) = \frac{e_{do}\ R_o^1}{e_{to}} + C_{30}\ A(3\ ,\ 3) + \frac{X_o^1\ e_{qo}}{e_{to}} + C_{40}\ A(6\ ,\ 3)$$

$$C(2\ ,\ 4) = C_{30}\ A(3\ ,\ 4) + C_{40}\ A(5\ ,\ 4)$$

$$C(2\ ,\ 5) = C_{30}\ (A(3\ ,\ 5) - w_o) + \frac{R_o^1\ e_{qo}}{e_{to}} + C_{40}\ A(5\ ,\ 5)$$

$$C(2\ ,\ 6) = \frac{e_{do}}{e_{to}}\ V_o C_{10} + C_{30}\ A(3\ ,\ 6) - \frac{e_{qo}}{e_{to}}\ V_o C_{20} + C_{40}\ A(5\ ,\ 6)$$

$$C(2\ ,\ 7) = C_{30}(A(3\ ,\ 7) - i_{qo}) + C_{40}(i_{do} + A(5\ ,\ 7))$$

$$C(2,8) = C_{30}\,A(3,8) + C_{40}\,A(5,8)$$

$$C(2,9) = C_{30}\,A(3,9) + C_{40}\,A(5,9)$$

$$C(2,10) = C_{30}\,A(3,10) + C_{40}\,A(5,10)$$

$$E(2,1) = C_{30}\,B(3,1) + C_{40}\,B(5,1)$$

$$E(2,2) = C_{30}\,B(3,2) + C_{40}\,B(5,2)$$

$$F(2,1) = \frac{e_{do}}{e_{to}}\,R_{30} + C_{30}\,D(3,1) + \frac{e_{qo}}{e_{to}}\,R_{40} + C_{40}\,D(5,1)$$

$$F(2,2) = \frac{e_{do}}{e_{to}}\,X_{30} + C_{30}\,D(3,2) + \frac{e_{qo}}{e_{to}}\,X_{40} + D(5,2)\,C_{40}$$

$$Z_o = \tan^{-1}(\,(X_q i_{qo} - i_{do} r)/e_{qo})$$

$$R_{30} = (V_o\,A_{10} - i_{qo}\,X)R_{20} + (V_o\,B_{10} + i_{do}\,X)\,R_{10}$$

$$X_{30} = (V_o\,A_{10} - i_{qo}\,X)X_{20} - (V_o\,B_{10} + i_{do}\,X)X_{10}$$

$$C_{30} = \frac{X_o^1\,e_{do}}{w_o\,e_{to}}$$

$$E_{10} = \frac{e_{qo}\,\mathrm{Sec}^2\,Z_o}{\tan Z_o}$$

$$R_{40} = (V_o\,A_{20} + i_{do}\,X)R_{20} + (V_o\,B_{20} + i_{qo}\,X)R_{10}$$

$$X_{40} = (V_o\,A_{20} + i_{do}X)X_{20} - (V_o\,B_{20} + i_{qo}\,X)X_{10}$$

2.3.7 Numerical values :

The final state equations are :

$$\dot{X} = AX + BU + DW$$
$$Y = CX + EU + FW \qquad (2.23)$$

where ,

$$A = w_o\ G_1^{-1}\ A_1$$

$$B = w_o\ G_1^{-1}\ B_1$$

$$D = w_o\ G_1^{-1}\ D_1$$

Machine parameters [9] :

$X_{md} = 1.0$ $X_{mq} = 0.6$ $X_d = 1.2$ $X_q = 0.8$ $X_{ffd} = 1.1$

$X_{kkd} = 1.1$ $X_{kkq} = 0.8$ $X_{d1} = 0.2$ $X_{f1} = 0.1$ $X_{kd1} = 0.1$

$X_{kq1} = 0.2$ $X_{fd} = 0.0011$ $r = 0.01$ $r_{kd} = 0.02$ $r_{kq} = 0.04$

$T_m = 6$ sec $k_d = 1.0$ $w_o = 314.0$

Voltage regulator parameters [9] :

$\tau_s = 2.0$ $\tau_e = 0.5$ $k_e = 40.0$ $k_s = 0.04$

Primemover and governor parameters [11] :

$\tau_g = 0.3$

Operating point :

The operating point values chosen for the system are:

Real power = 0.8 p.u.

Reactive power = 0.6 p.u. lagging

System frequency 'w_o' = 314.0 rad/sec.

Infinite bus voltage = 1.0 p.u.

Local load resistance = 1.6 p.u.

Local load reactance = 1.2 p.u. (Inductive)

The line parameters [9] :

The tie line resistance is neglected and the reactance is taken to be 0.25 p.u.

With the above data the system matrices are found as ;

$$
\begin{bmatrix}
-3.77 & 62.83 & & & & & & & 3.77 & \\
3.77 & -83.7 & -22.93 & -437.56 & 751.56 & 559.13 & 1.199 & & -3.77 & \\
 & -14.585 & -22.93 & -437.56 & 751.56 & 559.13 & 1.199 & & & \\
405.65 & 405.65 & -508.3 & -27.87 & -12.76 & 210.82 & 4.136 & & & \\
540.85 & 540.85 & -773.7 & -16.23 & -17.01 & 281.08 & 5.515 & & & \\
 & & & & & & 1.0 & & & \\
0.083 & 0.083 & -0.033 & 0.086 & 0.385 & & -0.167 & 0.167 & & \\
 & & & & & & & -1.0 & & \\
 & & & & & & & & -2.0 & -80.0 \\
 & & & & & & & & -0.04 & -2.1
\end{bmatrix}
$$

$$
B^T = \begin{bmatrix}
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & -80.0 & -1.6 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 1.0 & 0.0 & 0.0
\end{bmatrix}
$$

$$
D^T = \begin{bmatrix}
0.0 & 19.437 & 19.437 & -15.043 & -20.057 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 463.18 & 463.18 & -313.359 & -417.807 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0
\end{bmatrix}
$$

$$
C = \begin{bmatrix}
-0.157 & -0.146 & 0.128 & 0.3 & -0.299 & 1.45 & -0.002 & 0.0 & 0.0 & 0.0 \\
0.365 & 0.37 & -0.312 & 0.115 & -0.118 & -0.015 & 0.003 & 0.0 & 0.0 & 0.0
\end{bmatrix}
$$

$$
E = \begin{bmatrix}
0.0 & 0.0 \\
0.0 & 0.0
\end{bmatrix}
\qquad
F = \begin{bmatrix}
-0.007 & -0.193 \\
-0.019 & -0.416
\end{bmatrix}
$$

CHAPTER - 3

DESIGN OF CONTROLLERS

The discussions to follow present a systematic procedure for the design problem. Firstly a check for the existance of controllers of the kind discussed in chapter 2.2 is made. This is done by checking whether the conditions given by eqns. (2.3) are satisfied.

3.1 CHECK FOR CONTROLLABILITY :

Conditions given by eqns. (2.3) require the system to be stabilizable. The stabilizability is assured if the system is controllable. Thus we check for the controllability of the system under consideration.

The controllability for a system with distinct eigen values is obtained [1] iff no entire row of V^TB is identically zero ; where V is the matrix with the eigen vectors of A^T as the columns.

The required eigen vectors for the given system matrix A are calculated [12] and the product V^TB found.

Eigen values of the system matrix A :

$$-19.85768366 \quad + \quad j\ 313.13682556$$

$$-19.85768366 \quad - \quad j\ 313.13682556$$

$$-86.76879025$$

$$-27.88083959$$

-3.82955279

-1.00000119

-0.96654579

-0.05847392 + j 0.52290327

-0.05847392 - j 0.52290327

-0.26044716

$$V^T B = \begin{bmatrix} -0.00011917 + j\,0.00082067 & 0.00000044 + j\,0.0000046 \\ -0.00011917 - j\,0.00082067 & 0.00000044 - j\,0.0000046 \\ -0.74008161 & -0.00000484 \\ 0.053248 & 0.0 \\ -0.00011298 & 0.99999997 \\ 0.45947005 & 0.11687776 \\ 0.44152659 + j\,0.52290349 & -0.01207782 - j\,0.0653987 \\ 0.44152659 - j\,0.52290349 & -0.01207782 + j\,0.0653987 \\ -0.2394897 & 0.0 \end{bmatrix}$$

Clearly the system is controllable.

3.2 CHECK FOR THE RANK :

The matrix $\begin{pmatrix} A & B \\ C & E \end{pmatrix}$ for the system under consideration being a square matrix, its eigen values were calculated [12]. It was found that none of the eigen values are zero. This shows the rank of the matrix to be equal to the order (= n+m = n+r) of the matrix.

Eigen values of the matrix $\begin{pmatrix} A & B \\ C & E \end{pmatrix}$:

-19.857664	+	j 313.13678
-19.857664	-	j 313.13678
-86.768625		
-27.88143		
-3.3094957		
0.79184762	+	j 0.61496324
0.79184762	-	j 0.61496324
-1.5901205	+	j 0.54674523
-1.5901205	-	j 0.54674523
-0.4894694		
-0.39388661	+	j 0.40879213
-0.39388661	-	j 0.40879213

Thus it is ascertained that controllers of the type discussed in chapter 2.2 exist for the given system.

3.3 FEED BACK MATRIX CALCULATION :

The feed back matrix is obtained by optimal modal control theory as a sum of dyadic matrices. The dominant eigen values are devided into groups and for the pole assignment problem for each of the groups, dyadic feed back structure is assumed [2] .

The objective function for minimization for any particular group is taken as:

$$J = \sum_{i=1}^{m} \alpha_i^2 + \sum_{j=1}^{n} g_j^2 \qquad (3.1)$$

where,

$F = \underline{\alpha}\ \underline{g}^T$ is the feed back matrix corresponding to the group.

To shift the eigen values in group q after assignment of eigen values in the first (q-1) groups, the feed back matrix is [2] :

$$F^{(q)} = \underline{\alpha}^{(q)}\ \underline{g}^{(q)^T}, \quad (q=1,\ldots,p) \qquad (3.2)$$

where,

p represents number of groups

$$\underline{g}^{(q)} = \sum_{i=1}^{l_q} K_i^{(q)}\ \underline{V}_i^{(q)} \qquad (3.3)$$

$$K_i^{(q)} = \prod_{j=1}^{l_q} (\rho_j^{(q)} - \lambda_i^{(q)}) \Big/ \Big(V_i^{(q)^T} B\, \underline{\alpha}^{(q)} \prod_{\substack{j=1\\ j\neq i}}^{l_q} (\lambda_j^{(q)} - \lambda_i^{(q)})\Big) \qquad \ldots\ldots\ (3.4)$$

$\underline{V}_i^{(q)}$, $(i = 1,\ldots, l_q)$ are reciprocal eigen vectors of $A^{(q-1)}$ associated with eigen values $\lambda_i^{(q)}$, $(i = 1,\ldots, l_q)$ and

$$A^{(q)} = A + B \sum_{i=1}^{q} \underline{\alpha}^{(i)}\ \underline{g}^{(i)^T}, \qquad (3.5)$$

A is the system matrix and B the control matrix.

$\lambda_i^{(q)}$ and $\rho_i^{(q)}$, $(i = 1,\ldots,l_q)$ are the eigen values corresponding to the group q with l_q modes.

The $\alpha_i^{(q)}$, $(i = 1,\ldots, m)$ are so selected that the mode controllability condition

$$\underline{V}_i^{(q)^T} B \underline{\alpha}^{(q)} \neq 0 , \quad (i = 1,\ldots, l_q) \qquad (3.6)$$

is satisfied.

Negative gradient technique [2] is used for optimization and the resultant feed back matrix is calculated as :

$$K = \sum_{i=1}^{p} F^{(i)} \qquad (3.7)$$

3.3.1 Grouping criterion [2] :

To obtain low feed back gains, each pair of complex conjugate eigen values are shifted in a group. The real eigen values are grouped such that the vectors $\underline{V}_i^{(q)}$, $(i=1,\ldots,l_q)$ are confined within as narrow a cone as possible. Furthermore, the projections of the vectors $\underline{V}_i^{(q)}$, $(i=1,\ldots,l_q)$ on the space spanned by the columns of B matrix are as large as possible.

3.3.2 Algorithm for optimal modal controller design using grouping criterion :

(i) Determine the augmented system and control matrices $\bar{A}$ and $\bar{B}$ respectively of eqn. (2.7).

(ii) Determine the dominant eigen values of the system matrix $\bar{A}$ and select new locations for them.

(iii) If there are repeated eigen values displace them to different locations by applying a suitable state feed back, so as not to effect much the mondominant eigen values.

(iv) Set $q = 1$.

(v) Calculate the normalized left eigen vectors and eigen values of $\bar{A}^{(q-1)}$.

(vi) Form the q^{th} group using the grouping criterion.

(vii) Initialize $\underline{\alpha}^{(q)}$ by checking the mode controllability condition.

(viii) Set the objective function value J to a large value.

(ix) Calculate $K_j^{(q)}$, $(j=1,\ldots,l_q)$ and $\underline{g}^{(q)}$ from eqns. (3.4) and (3.3).

(x) Calculate the new objective function value.

(xi) If $|J_{new} - J_{old}| \leqslant \epsilon$ (a small specified positive number) go to step (xiii) otherwise renew the objective function value.

(xii) Change $\underline{\alpha}^{(q)}$ as $\underline{\alpha}^{(q)}_{new} = \underline{\alpha}^{(q)} + c(\Delta\underline{\alpha}^{(q)})$ where c is step length and $\Delta\underline{\alpha}^{(q)}$ is the negative of the gradient of $J^{(q)}$ with respect to $\underline{\alpha}^{(q)}$ [2]. Check whether the mode controllability criterion for the

modes of the group is satisfied by the new $\underline{\alpha}^{(q)}$ vector. If it is not satisfied then reduce c appropriately to satisfy the criterion and go to step (ix).

(xiii) Calculate the modal controller matrix $F^{(q)}$ and $A^{(q)}$.

(xiv) If q = p go to (xv); else increment q by 1 and go to (v).

(xv) Calculate the modal controller matrix K from eqn. (3.7).

(xvi) Stop.

3.4.1 Eigen values of the augmented system matrix :

-19.857645 + j 313.13678

-19.857645 - j 313.13678

-86.76832

-27.880851

-3.839552

-1.0000009

-0.96722747

-0.0584884 + j 0.52292036

-0.0584884 - j 0.52292036

0.0

0.0

3.4.2 New locations for the dominant eigen values :

-2.3 + j 0.5229, -2.3 - j 0.5229, -2.2, -1.9, -1.8,

3.4.3 Optimal modal controller matrix :

$$K = \begin{bmatrix} 1.5263 & 1.4249 & -1.491 & 3.615 & -2.6862 & 180.9302 & 167.4762 & 9.4585 & 0.2088 & -9.3258 & 66.0895 & -22.7707 \\ -1.5263 & -1.4249 & 1.491 & -3.615 & 2.6862 & -180.9302 & -167.4762 & -9.4585 & -0.2088 & 9.3258 & -65.0895 & 23.7707 \end{bmatrix}$$

3.5 Controller schemes for given system (2.23) :

The matrices K_1, K_2 , K_3 are computed from equations 2.8 and 2.10.

$$K_1 = \begin{bmatrix} 1.5263 & 1.4249 & -1.491 & 3.615 & -2.6862 & 180.9302 & 167.4762 & 9.4585 & 0.2088 & -9.3258 \\ -1.5263 & -1.4249 & 1.491 & -3.615 & 2.6862 & -180.9302 & -167.4762 & -9.4585 & -0.2088 & 9.3258 \end{bmatrix}$$

$$K_2 = \begin{bmatrix} 66.0895 & -22.7707 \\ -65.0895 & 23.7707 \end{bmatrix}$$

$$K_3 = \begin{bmatrix} -0.9476 & -22.9093 \\ 0.9691 & 23.4793 \end{bmatrix}$$

CHAPTER - 4

SYSTEM PERFORMANCE

Constant disturbance of 0.0625 p u in load resistance and 0.0833 p u in load reactance is applied. The performance of the uncontrolled system and the system with various controllers are obtained by digital simulation. Runge-Kutta 4^{th} order [11] method is used for the solution of the problem. The system responses for different cases are given in Figs. 4.1,...,4.5.

The regulator designs reported are preliminary designs. The eigen value locations are chosen rather arbitrarily. The eigen value locations have to be so chosen that the regulator response is satisfactory and no component of the regulator goes in to saturation for the usual system disturbances. This requirement imposes the extent to which eigen values may be shifted in the left half plane. It is also desirable to limit the feed back gains. The responses of the system with the regulators seem to be a little slow. The performances can be improved further by shifting the eigen values further in to the left half plane. For a practical design satisfactory locations for the eigen values can be chosen by trial and error considering the above-mentioned limitations.

CHAPTER - 5

CONCLUSION

A power system network consisting of a generator with a local load connected to an infinite bus system by a tie line was considered for regulator and stabilizer design. A stabilizer was designed using state feed back to improve the dynamic characteristic of the system. Three types of regulators, (i) integral feed back , (ii) feed forward and (iii) feed forward in combination with integral feed back were designed for asymptotic rejection of constant disturbances in the local load from the infinite bus system and to obtain voltage regulation at the generation bus. An appropriate linearized model of the given system was developed and optimal modal control theory with grouping criterion was used for the design of controllers with optimum controller parameters. The system performances were obtained with various controllers for a constant disturbance.

In our design we have considered complete state feed back which needs all the system states to be measurable. Alternately we need to design an observer to obtain the unmeasurable states. It may be possible to obtain a simpler controller by using incomplete state feed back [13].

The class of disturbances considered for the design consists of constant disturbances only. In an actual system the disturbances are of arbitrary nature. Design techniques

are available in literature for rejection of certain classes of disturbances. For rejection of polynomial disturbances the control scheme becomes more complex as compared to that for constant disturbances and the complexity increases with increase in the order of the polynomial. In case of a power system problem it may not be of much use to implement regulators for rejection of polynomial disturbances.

The work here considers a single generator to infinite bus through a tie line. The design technique can be extended for a more realistic network with multimachine systems. Regulators can be designed with the guide-line given in the work for sharing a given load in various desired proportions and steady state load flow in different links of a power system network can be controlled accordingly.

The representation of load considered here would be inadequate in practical situations. The work can be extended by considering a more realistic load models.

Wide range modal controllers can be designed [2] for reduction of sensitivity of controllers to change in operating point of the system. Accessible state feed back schemes can be tried to obtain simpler controller schemes.

In the design the system performance equations are linearized about an operating point and controller schemes are designed to improve the performance of this system for small disturbances. It is worth studying the performance of nonlinear model with the linear regulator for large disturbances.

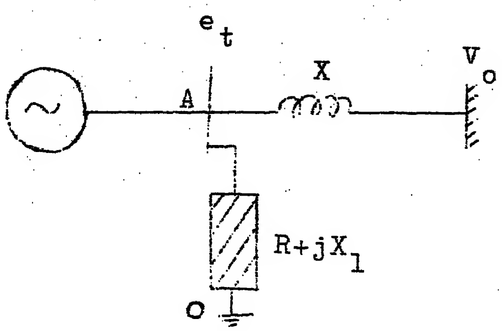

Fig. 2.1. Power System

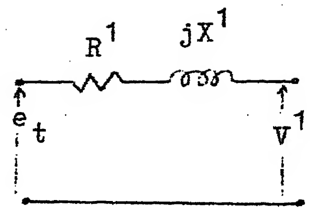

Fig. 2.2. Thevenin equivalent circuit of terminal network

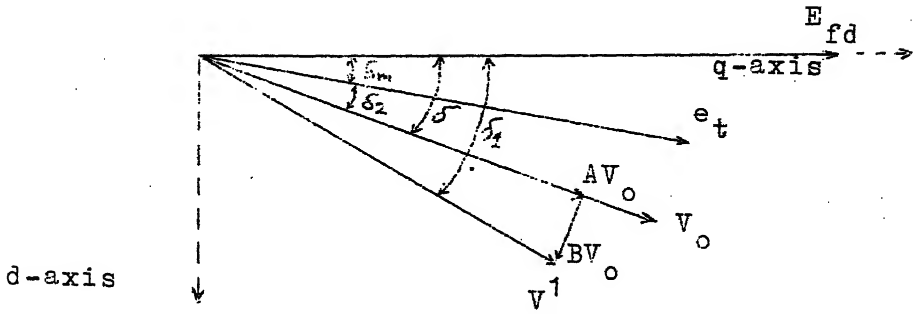

Fig. 2.3. Load angle diagram

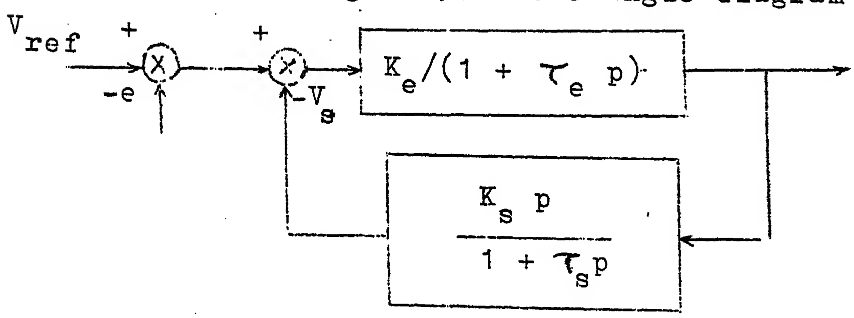

Fig. 2.4. Voltage regulator representation

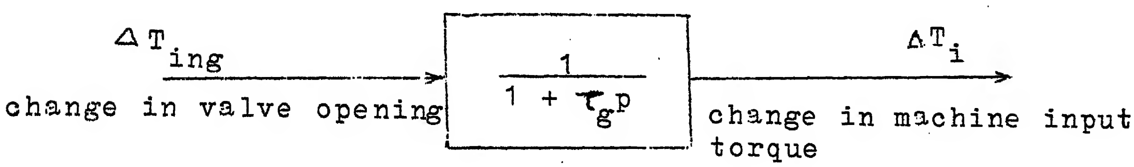

Fig. 2.5. Governor and primemover representation

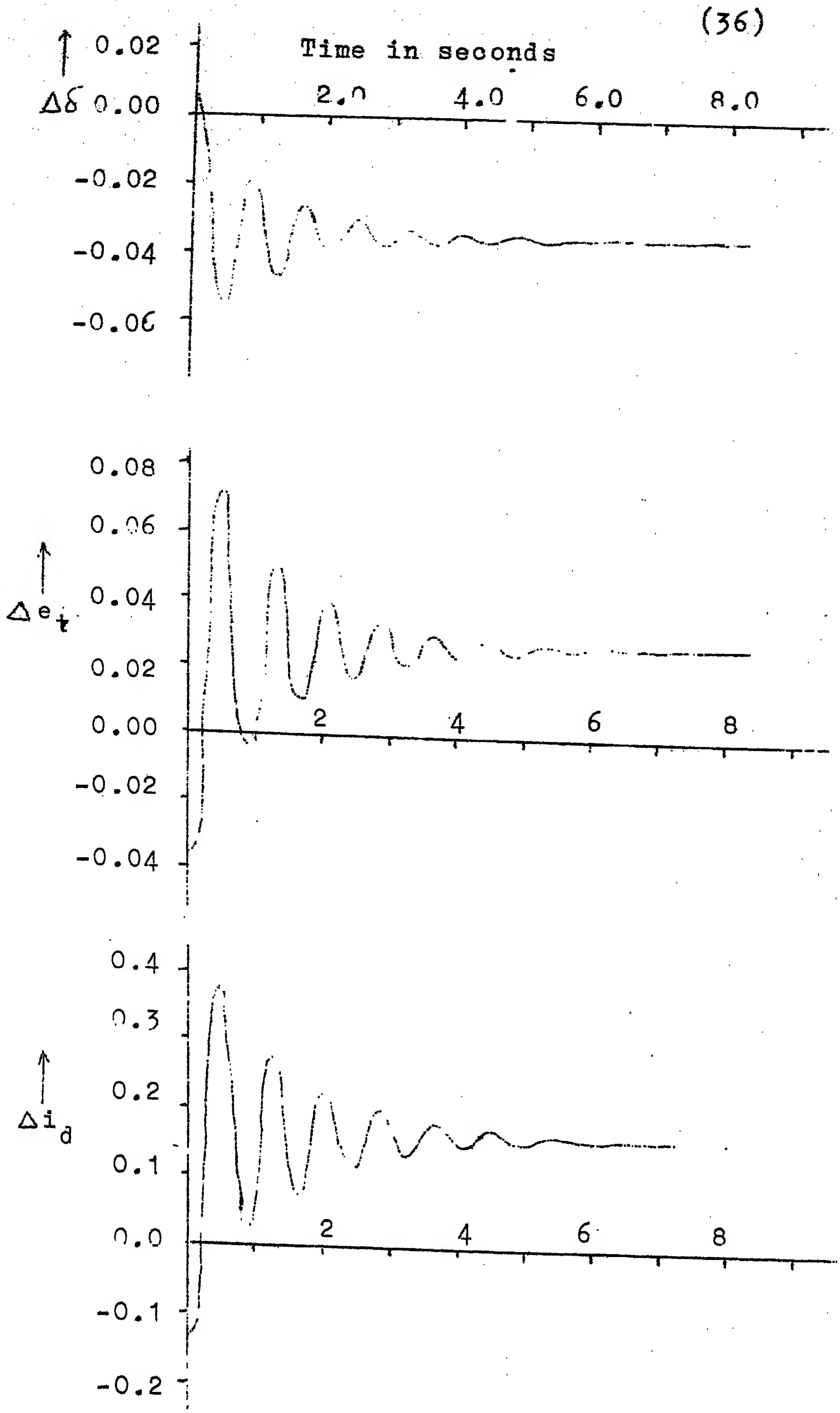

Fig. 4.2 SYSTEM RESPONSE WITH STATE FEEDBACK
($U = K_1X$)

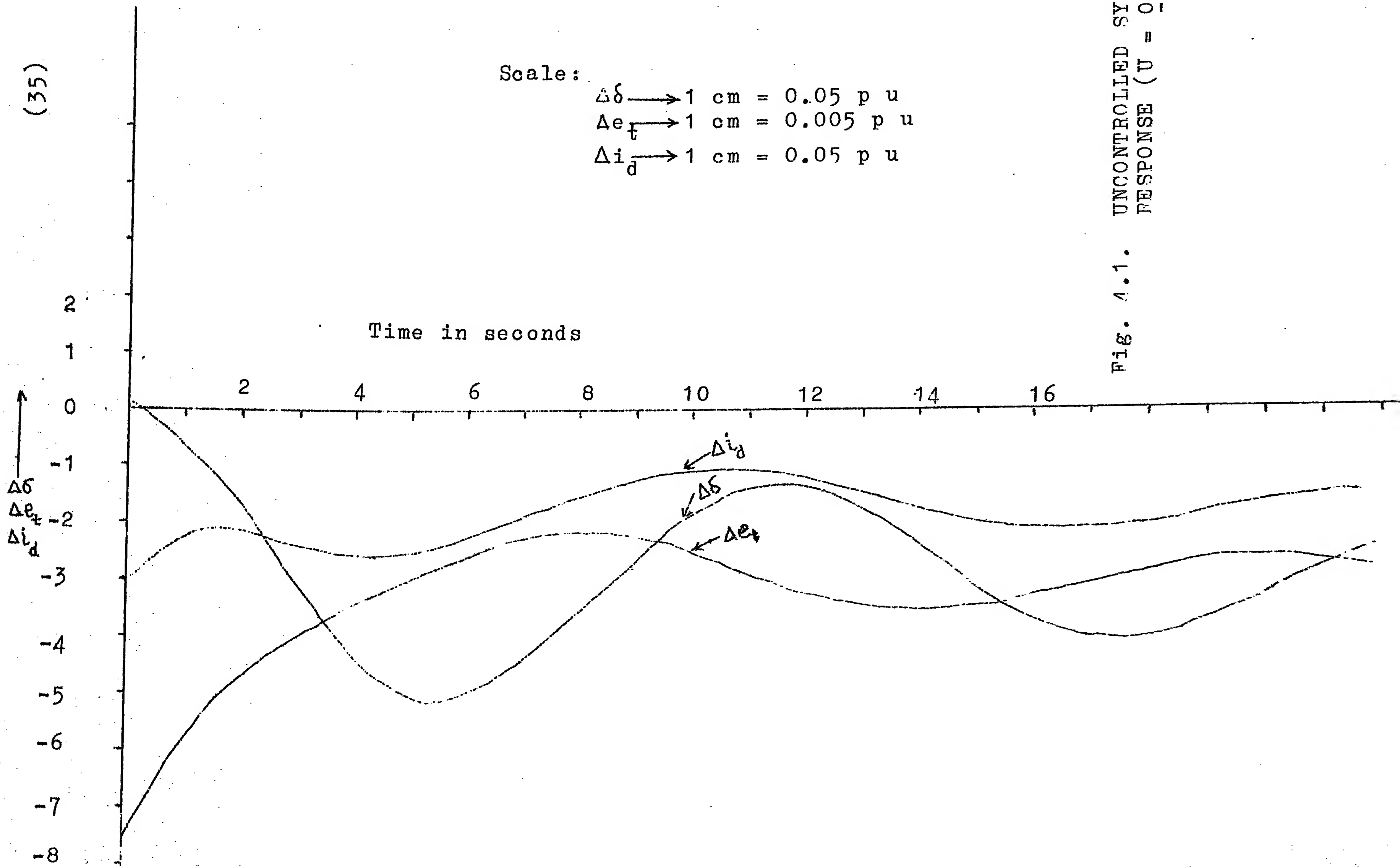

Fig. 4.1. UNCONTROLLED SYSTEM RESPONSE (U = 0)

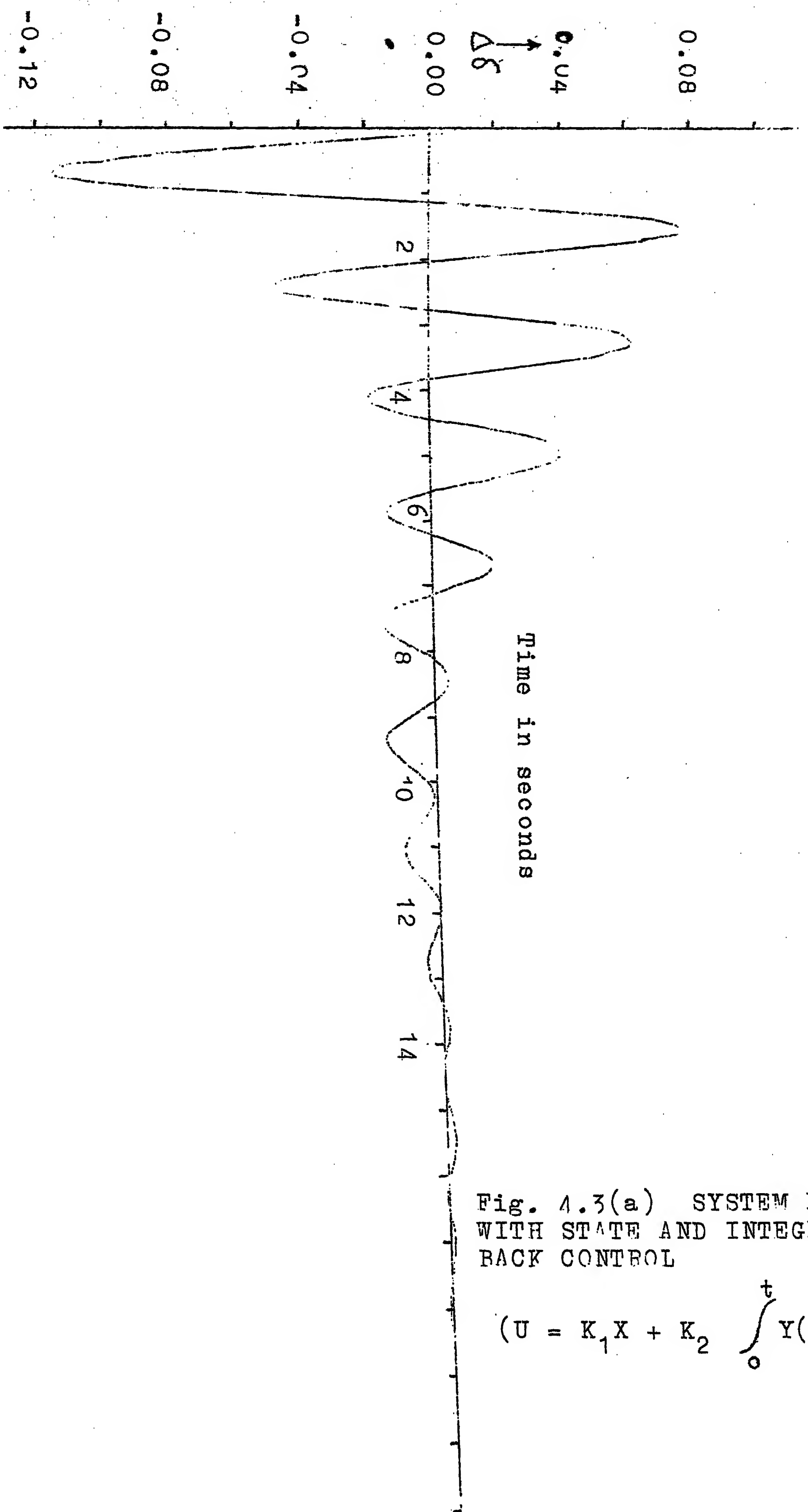

Fig. 4.3(a) SYSTEM RESPONSE WITH STATE AND INTEGRAL FEED-BACK CONTROL

$$\left(U = K_1 X + K_2 \int_0^t Y(s)\,ds\right)$$

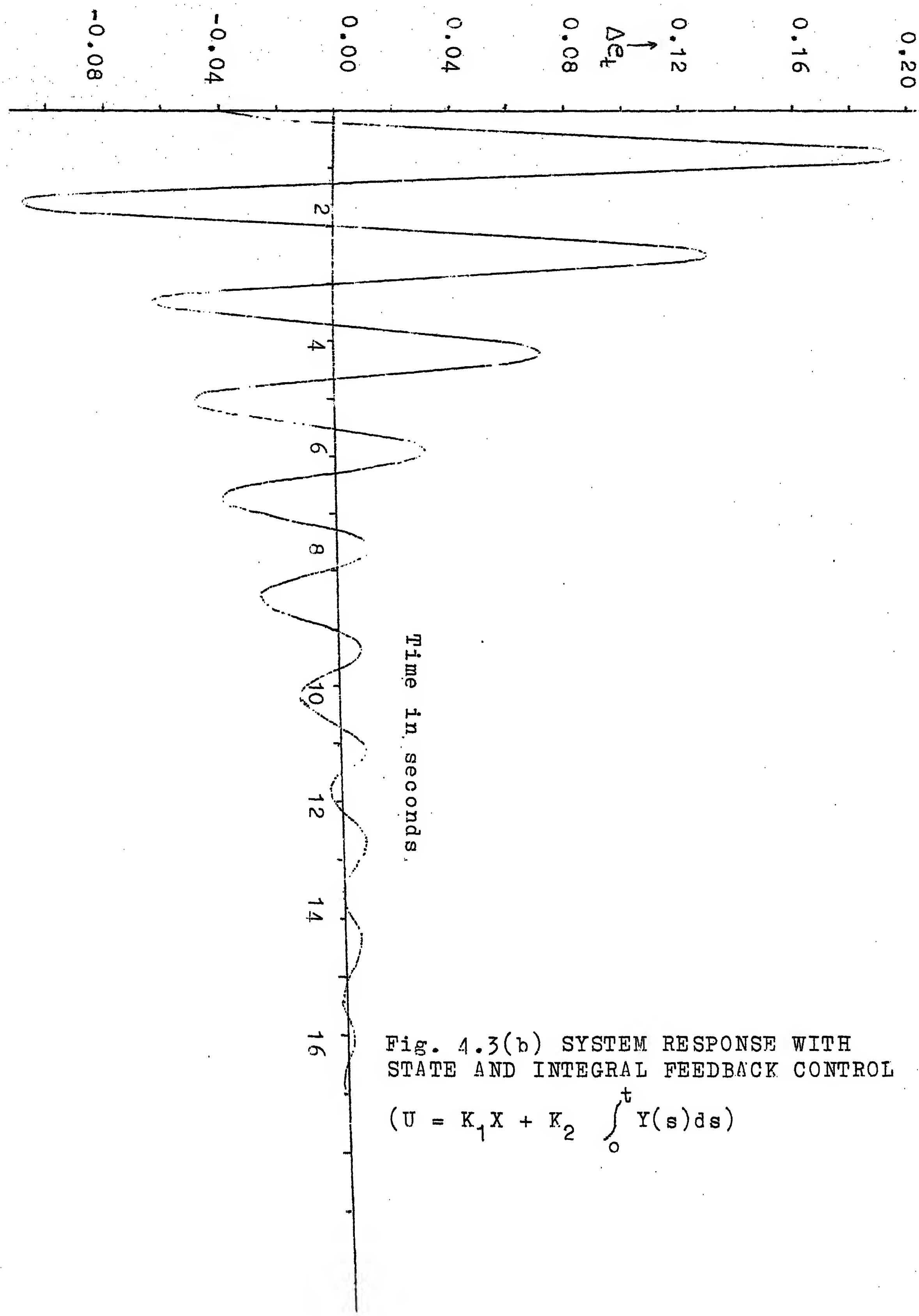

Fig. 4.3(b) SYSTEM RESPONSE WITH STATE AND INTEGRAL FEEDBACK CONTROL

$(U = K_1 X + K_2 \int_0^t Y(s)\,ds)$

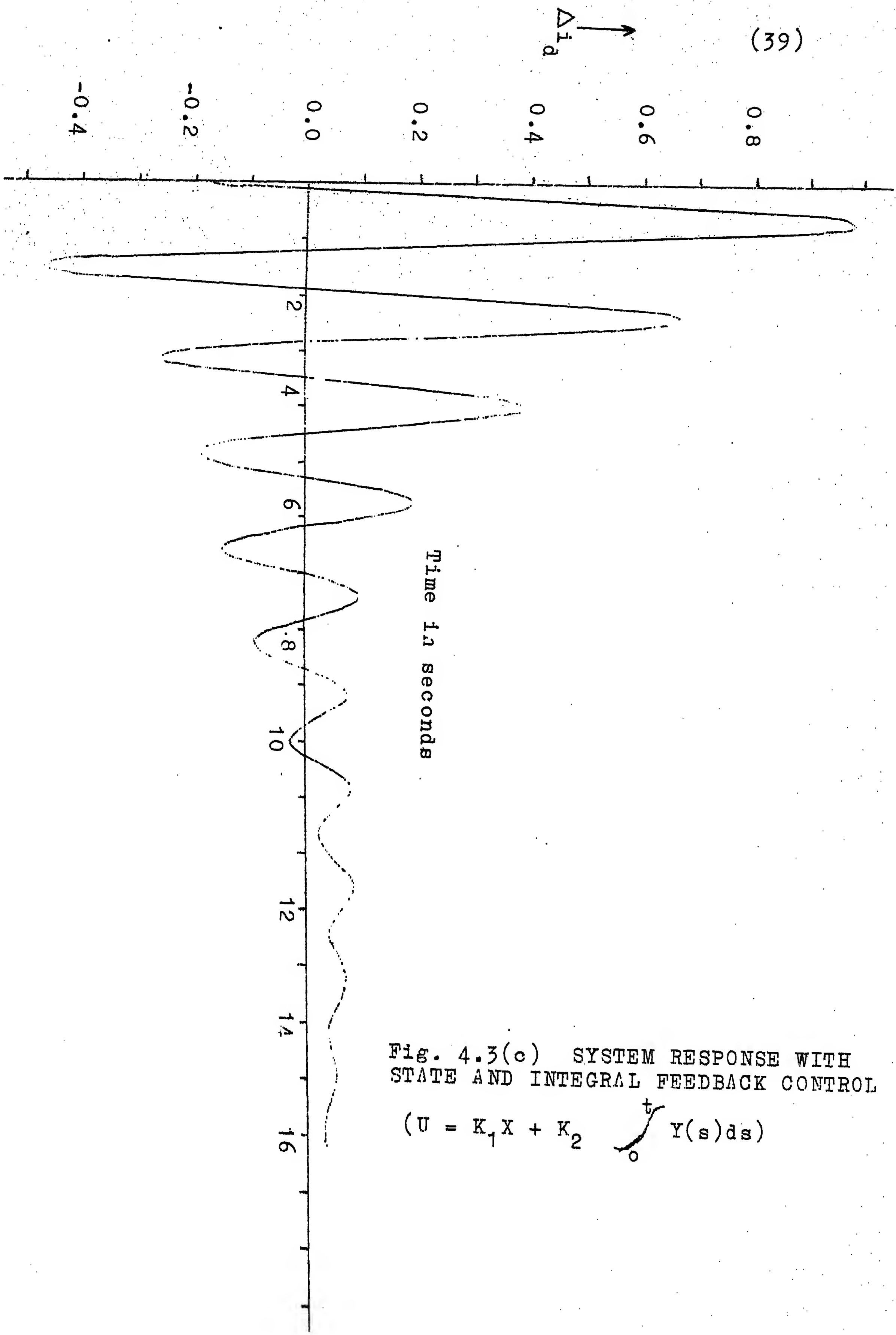

Fig. 4.3(c) SYSTEM RESPONSE WITH STATE AND INTEGRAL FEEDBACK CONTROL

$$(U = K_1 X + K_2 \int_0^t Y(s)ds)$$

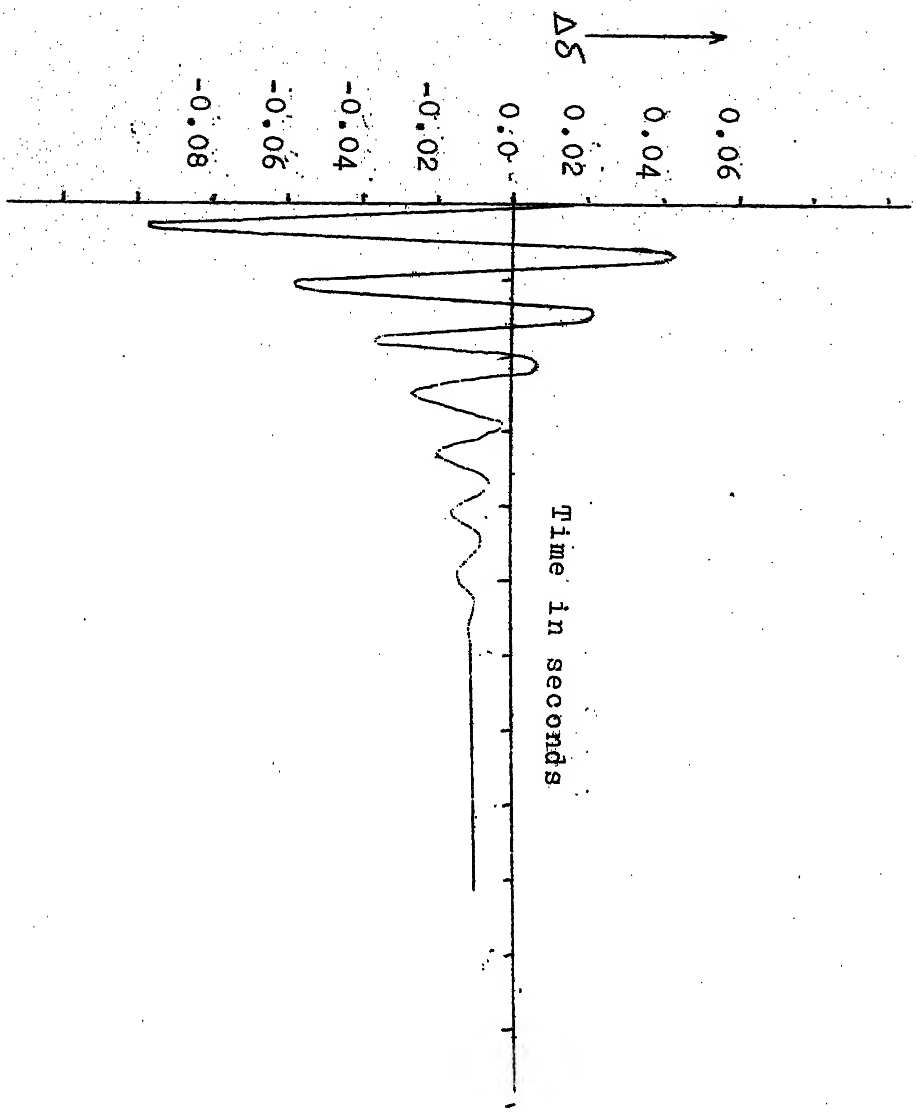

Fig. 4.4.(a) SYSTEM RESPONSE WITH STATE FEEDBACK AND FEEDFORWARD CONTROL ($U = K_1X + K_3W$)

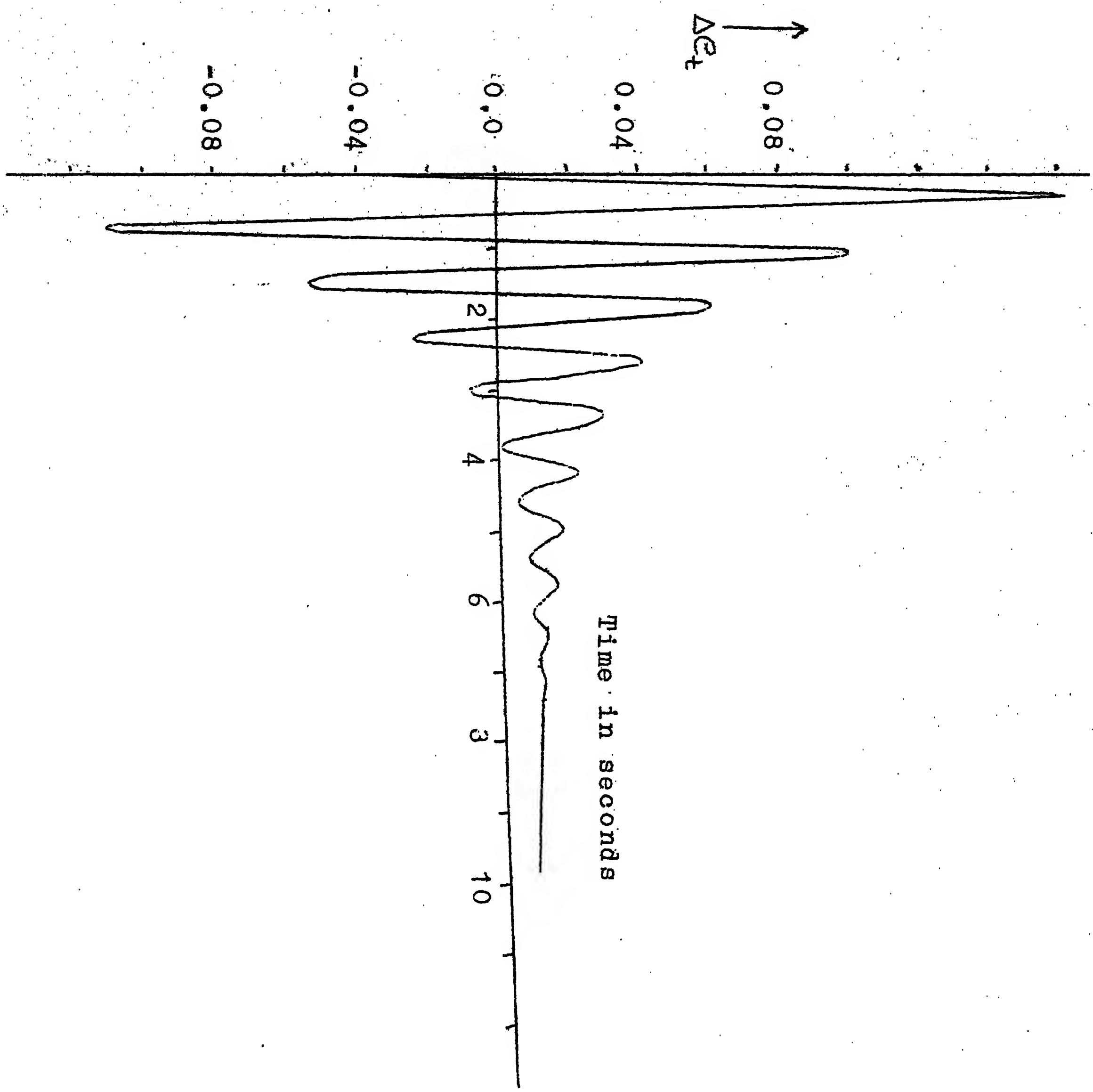

Fig. 4.4.(b) SYSTEM RESPONSE WITH STATE FEEDBACK AND FEEDFORWARD CONTROL $(U = K_1X + K_3W)$

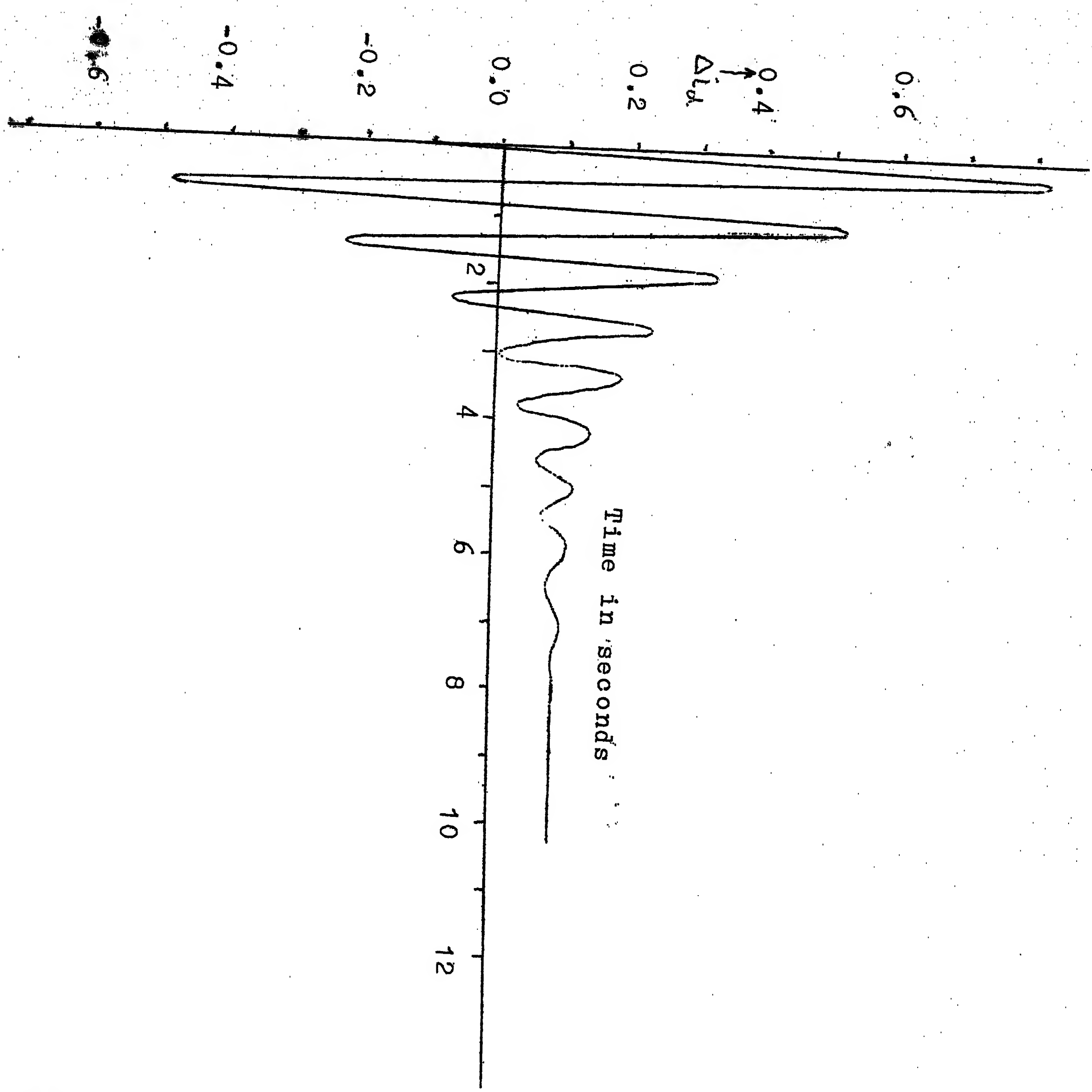

Fig. 4.4.(c) SYSTEM RESPONSE WITH STATE FEEDBACK AND FEEDFORWARD CONTROL
($U = K_1X + K_3W$)

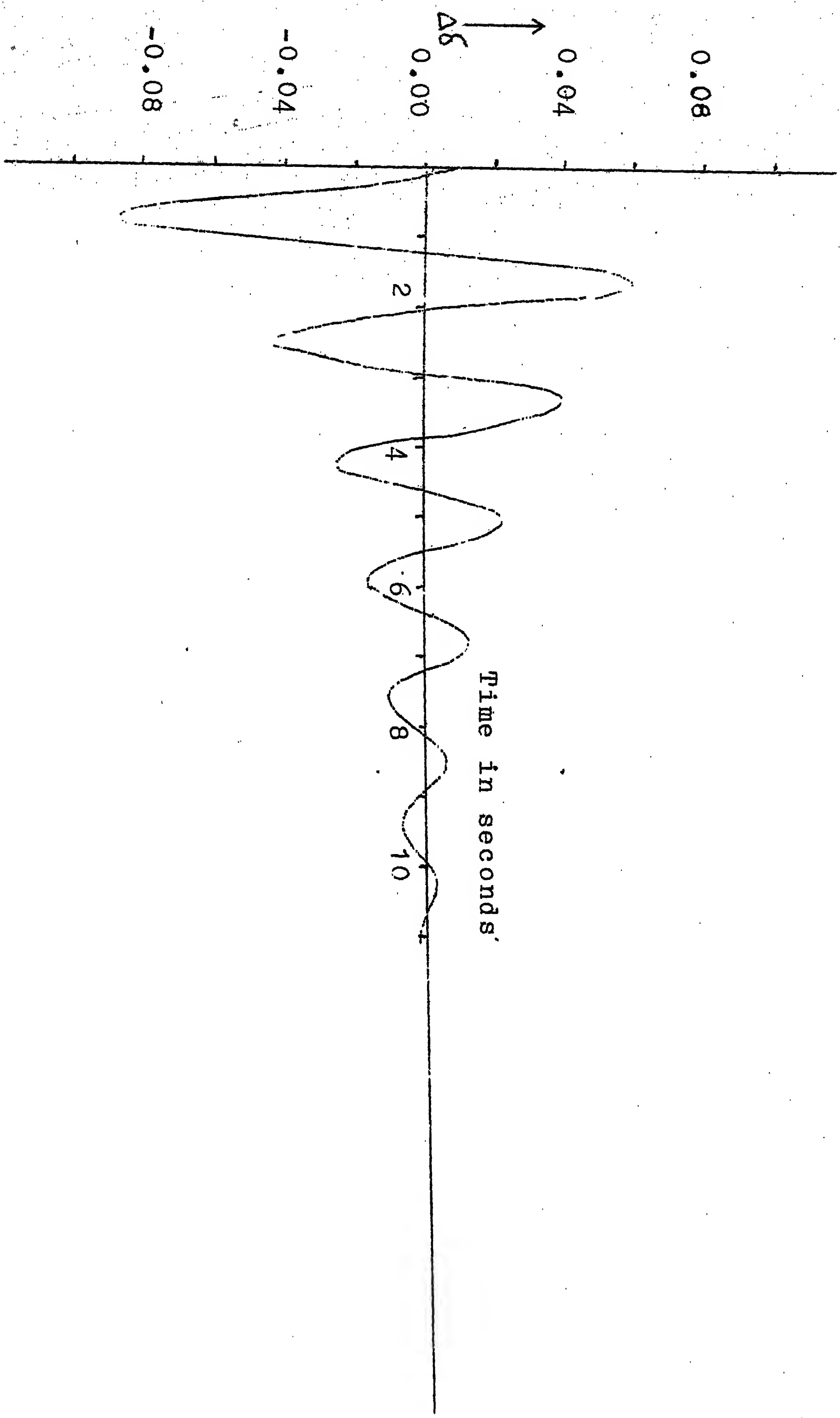

Fig. 4.5(a) SYSTEM RESPONSE WITH STATE FEEDBACK, FEEDFORWARD AND INTEGRAL FEEDBACK CONTROL

$$(U = K_1 X + K_2 \int_0^t Y(s)ds + K_3 W)$$

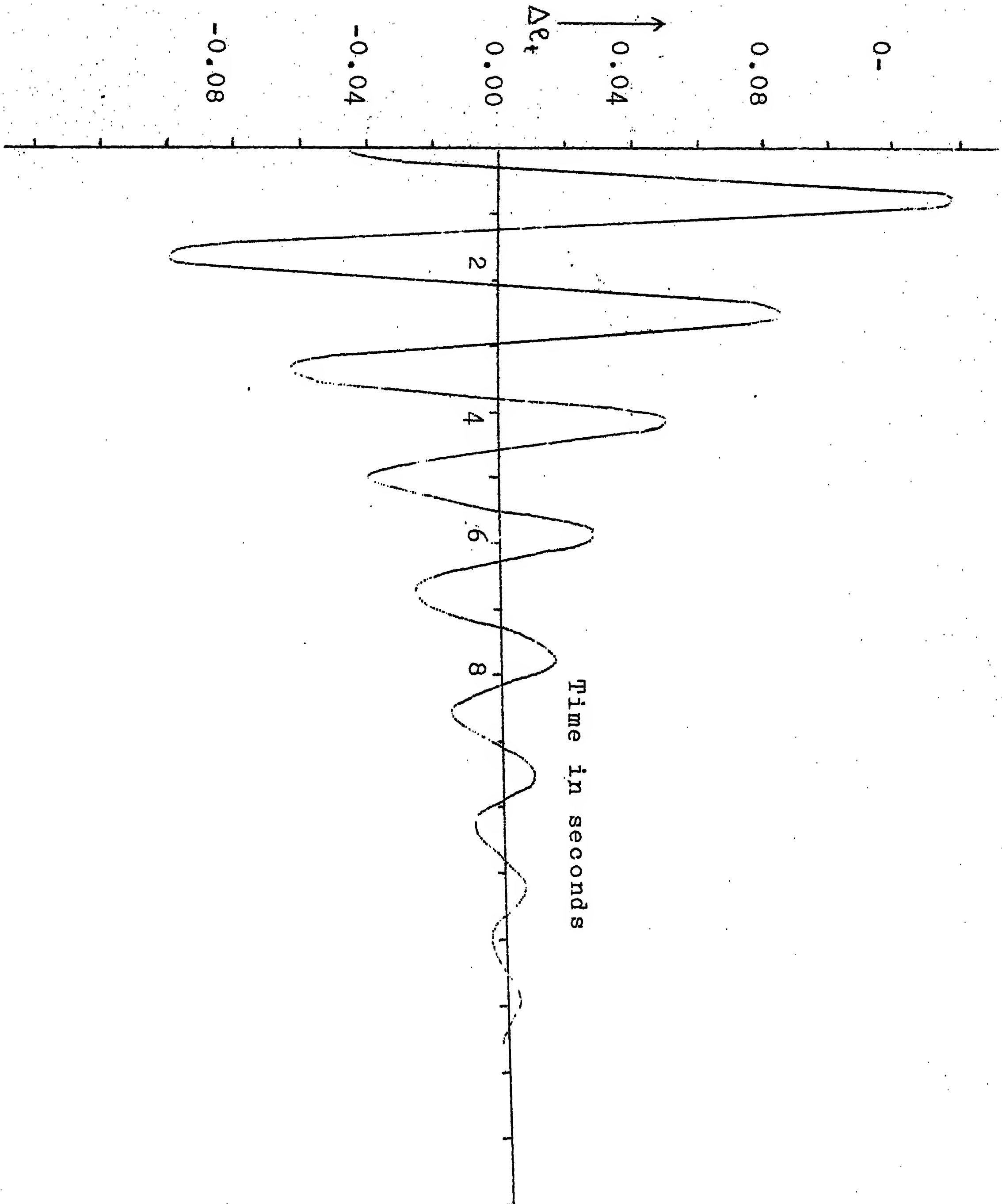

Fig. 4.5(b) SYSTEM RESPONSE WITH STATE FEEDBACK, FEEDFORWARD AND INTEGRAL FEEDBACK CONTROL

$$(U = K_1 X + K_2 \int_0^t Y(s)ds + K_3 W)$$

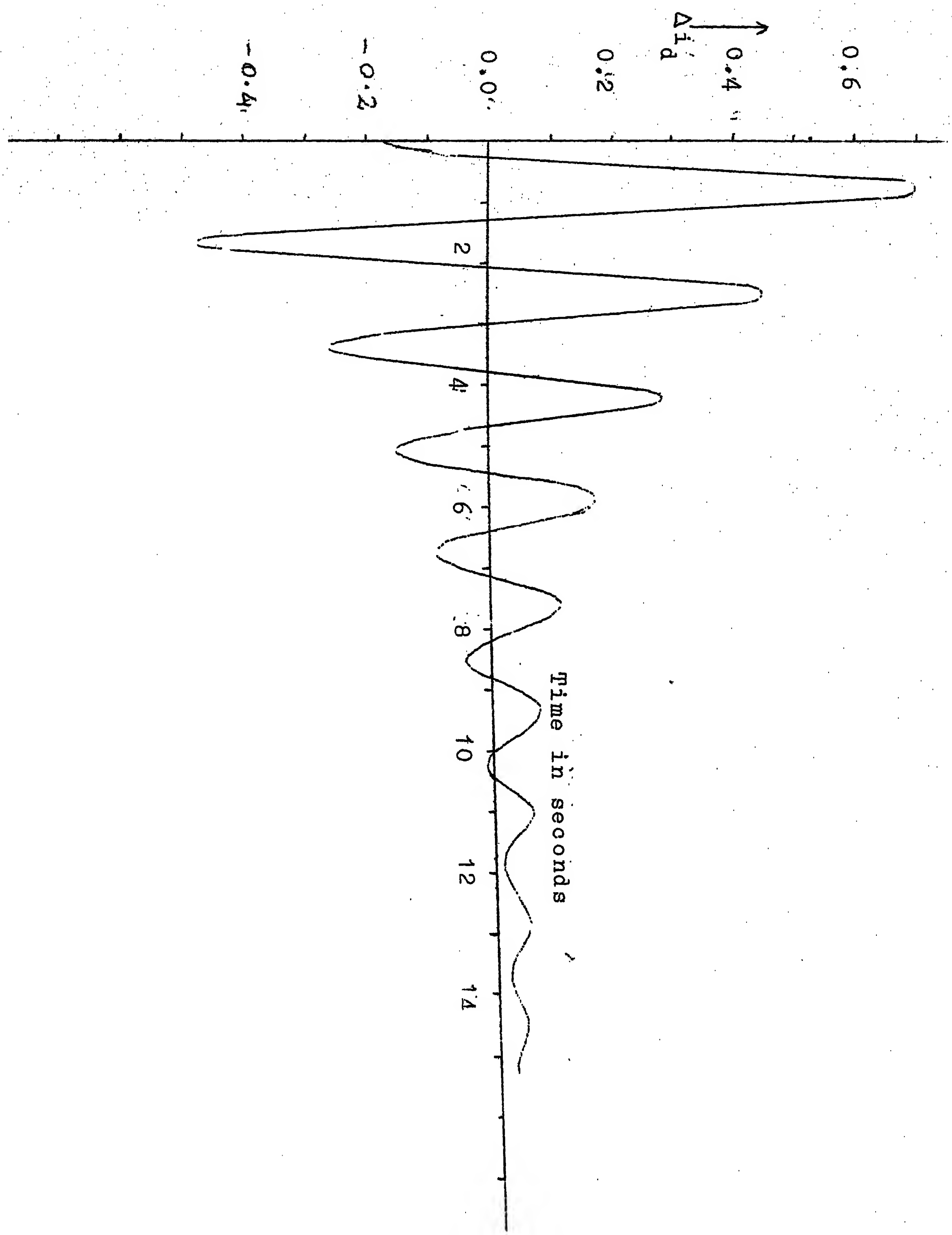

Fig. 4.5(c) SYSTEM RESPONSE WITH STATE FEEDBACK, FEEDFORWARD AND INTEGRAL FEEDBACK CONTROL

$$(U = K_1 X + K_2 \int_0^t Y(s)ds + K_3 W)$$

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CERTIFICATE

It is certified that this work entitled 'Regulator design for a power system with constant local load disturbances' by N.K. Patel has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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